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Spin Transparency Method for High Precision Experiments with Polarized Beams

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Outline

1. Concept of Spin Transparency (ST) method
2. Spin Navigators based on weak solenoid and dipole fields
3. Possibilities of experimental verification of ST mode in existing synchrotrons
4. ST mode for high precision experiments
5. ST method at ultra-high energies
6. Conclusion

Motivation

- Experiments with polarized beams have been and remain a crucial tool in understanding particle and nuclear structure and reactions from the first principles
- Knowledge of the spin orientation is necessary for a complete description of the dynamical particle state
- Polarized beams enable search for new physics beyond the Standard Model with high-precision
- Study of the nucleon spin structure is one of the main goals of the modern nuclear physics

We present the **Spin Transparency method** for precise control of the longitudinal and transverse polarizations in colliders and storage rings

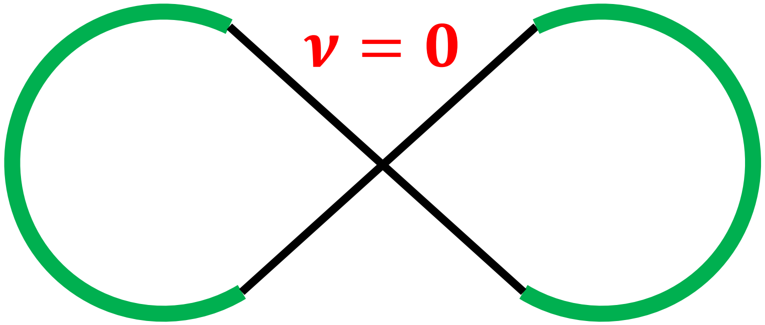
Spin Transparency (ST) method

The ST concept is based on the use of a ring structure where the **magnetic elements return an arbitrarily-directed spin to its original orientation** after a single particle turn around the collider, i.e. the structure is transparent to the spin.

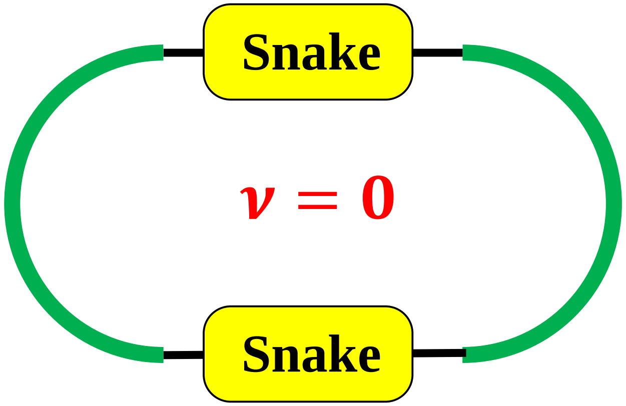
In the ST mode, the particles are technically in the region of a spin resonance (ST resonance) where the spin motion is highly sensitive to small perturbations in magnetic fields. This allows for **flexible control of the polarization direction by Spin Navigators** (**SN**) based on weak fields.

For stability of the spin dynamics, the spin effect of the **navigator fields must significantly exceed** that due to **imperfections and misalignments** of the collider elements as well as the effect due to the orbital beam emittances.

Examples of ST rings



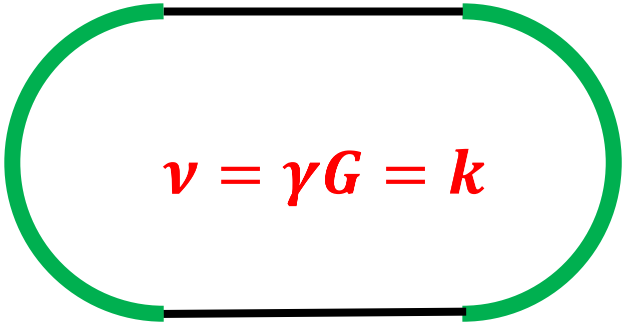
A **figure-8** ring provides ST mode at arbitrary energy for any particle species.



A **racetrack** ring with **two identical Siberian snakes** provides ST mode at arbitrary energy

NICA(JINR) - protons, deuterons

RHIC (BNL) - protons.

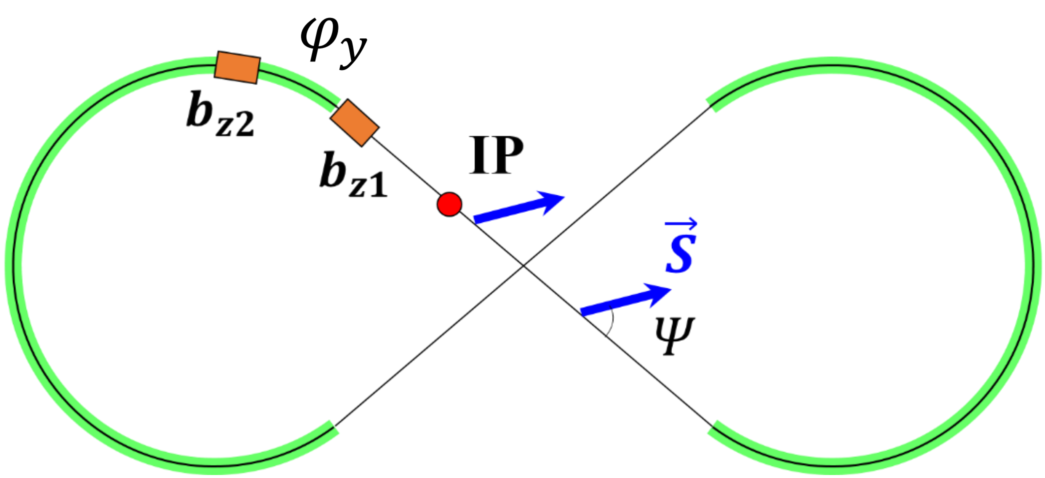


A racetrack ring without snakes provides ST mode at **certain energies corresponding to integer spin resonances**.

COSY (FZJ), Nuclotron (JINR) -protons

RHIC (BNL) - deuterons.

Spin Navigator based on two weak solenoids



$$\frac{b_{z1}L_z}{B\rho} = \frac{2\pi\nu_{nav}}{1+G}\frac{\sin(\varphi_y-\Psi)}{\sin(\varphi_y)}$$

$$\frac{b_{z2}L_z}{B\rho} = \frac{2\pi\nu_{nav}}{1+G}\frac{\sin(\Psi)}{\sin(\varphi_y)}$$

$\boldsymbol{b_{z1}, b_{z2}}$ are the SN solenoid fields,
$\boldsymbol{B\rho}$ is the magnetic rigidity,
$\boldsymbol{\nu_{nav}}$ is the spin navigator tune,
$\boldsymbol{\varphi_y = \gamma G\alpha}$ is the spin rotation angle between the weak solenoids,
$\boldsymbol{\alpha}$ is the orbit rotation angle between the weak solenoids,
$\boldsymbol{\Psi}$ is the desired angle between the spin and beam velocity in the collider's plane

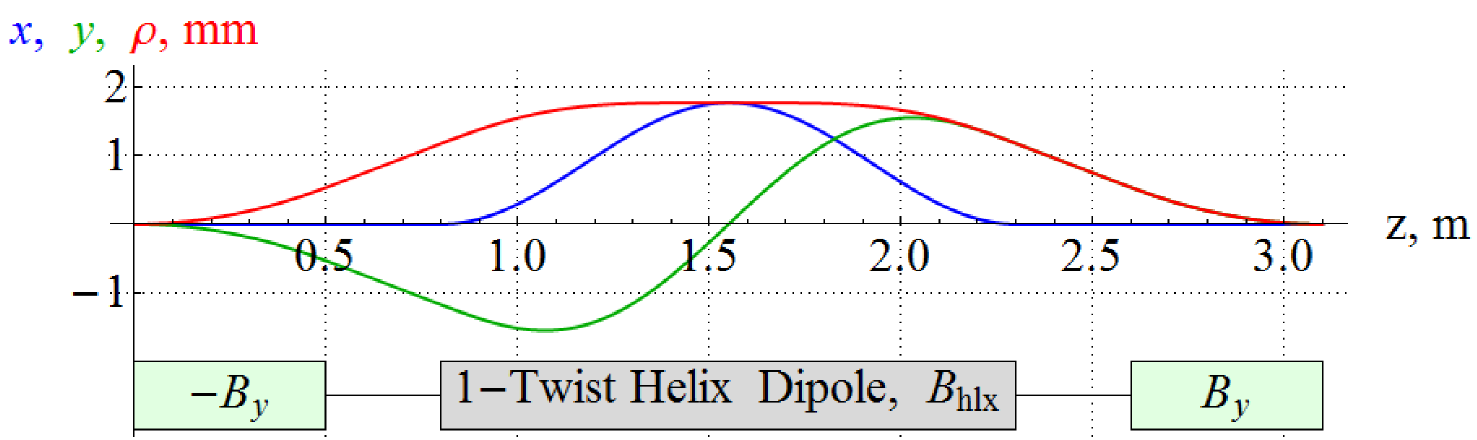
For maintaining the navigator tune, the required **field integrals** of the solenoids **grow proportionally to the beam momentum**

A field integral of **up to 10 T·m** is sufficient to control **proton** and **deuteron** polarizations in the momentum range of **up to 100 GeV/c**

Spin Navigator with two helical magnets

The net spin rotation axis of a helical magnet with a small field integral is practically longitudinal. This allows for **replacement of solenoids with helical magnets** in SN designs for **high energies**

$\boldsymbol{\nu_{\mathrm{nav}} = 0.01}$: $L_y = 0.5\text{m}$, $L_{\mathrm{hlx}} = 1.5\text{m}$, $L_{\mathrm{tot}} = 3.1\text{m}$, $B_y = 0.3\text{T}$, $B_{\mathrm{hlx}} = 1.0\text{T}$



The transverse closed orbit deflection does not exceed 2 mm at 20 GeV/c

A transverse field integral of **1.8 T·m** per magnet is required **independent of the beam energy** for $\nu_{\mathrm{nav}} = 0.01$.

ST Resonance Spin Field

The ST resonance spin field

$$\vec{\omega} = \vec{\omega}_{\text{coh}} + \vec{\omega}_{\text{emit}},$$

- the **coherent part** of the ST resonance field $\vec{\omega}_{\text{coh}}$ is related to magnet imperfections and misalignments
- the **incoherent part** of the ST resonance field $\vec{\omega}_{\text{emit}}$ has to do with betatron and synchrotron particle oscillations and is proportional to the orbital beam emittances

In practice, the coherent part of the ST resonance strength $\boldsymbol{\omega}_{\textbf{coh}}$ **significantly exceeds the strength of the** incoherent part $\boldsymbol{\omega}_{\textbf{emit}}$

$$\omega_{\text{emit}} \ll \omega_{\text{coh}}$$

The field $\vec{\boldsymbol{\omega}}_{\textbf{coh}}$ does not lead to depolarization of the beam. It only coherently rotates the spins about an a priori unknown direction $\vec{\omega}_{\text{coh}}$ by an angle $2\pi\omega_{\text{coh}}$.

Spin Stability Conditions

The spin tune ν_{nav} induced by the SN must significantly exceed the ST-resonance strength ω

$$\nu_{\text{nav}} \gg \omega$$

In the ST mode at integer spin resonances, one must consider the constraints imposed on the navigator fields by synchrotron oscillations, which cause satellite resonances

$$\bar{\nu} \equiv \bar{\gamma} G = k + m_s \nu_s, \qquad \gamma = \bar{\gamma} + \Delta\gamma,$$

where ν_s is the synchrotron tune, $\bar{\gamma}$ is the relativistic factor averaged over the synchrotron oscillations, $\Delta\gamma$ is the energy spread, and m_s is the satellite spin resonance number.

Implementation of the **additional condition**

$$\nu_{\text{nav}} \gg \max(\Delta\nu, \nu_s)$$

overcomes the effect of satellite resonances on the spin dynamics. Here $\Delta\nu = G\Delta\gamma$ is the spin tune spread.

Experimental verification of ST mode in RHIC

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EXPERIMENTAL VERIFICATION OF TRANSPARENT SPIN MODE IN RHIC*

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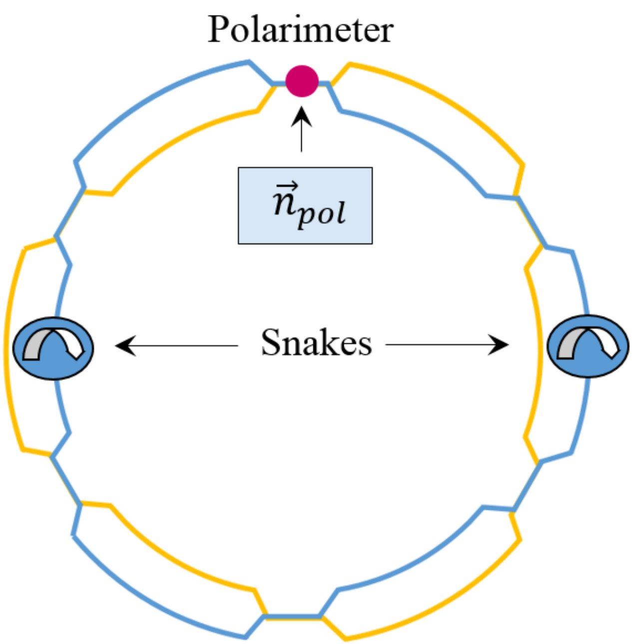
CONCLUSION

A new mode of RHIC operation with a polarized proton beam, a transparent spin mode, has been proposed. It offers new opportunities for manipulation of the proton polarization at any location in the collider. BNL's RHIC has all of the necessary components for an experimental test of the new mode. Potential experimental scenarios have been presented. Experimental parameters are being developed [15]. The experiment will validate the TS concept as a new tool for polarization preservation and control in the existing and future synchrotrons.



ST mode at integer spin resonances

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Hadron polarization control at integer spin resonances in synchrotrons using a spin navigator

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Highlights from Conclusion

- Use of the ST mode presents a **unique opportunity to control the deuteron polarization in RHIC** where application of full Siberian snakes and strong spin rotators is not practical
- The proposed **spin navigator is universal** and can be used to **control the polarizations of deuteron, proton and helium-3** beams in the ST modes of the existing and future machines such as NICA, EIC, EicC in China, and COSY in Germany

COSY Proposal: Spin transparency experiments for proton polarization control at integer spin tune resonances

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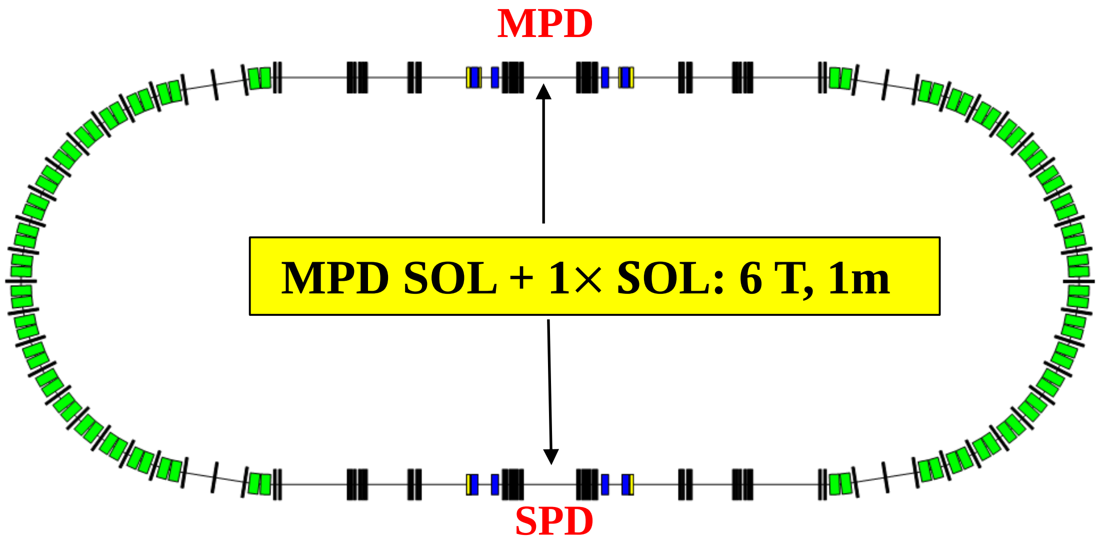
(2022-2024)

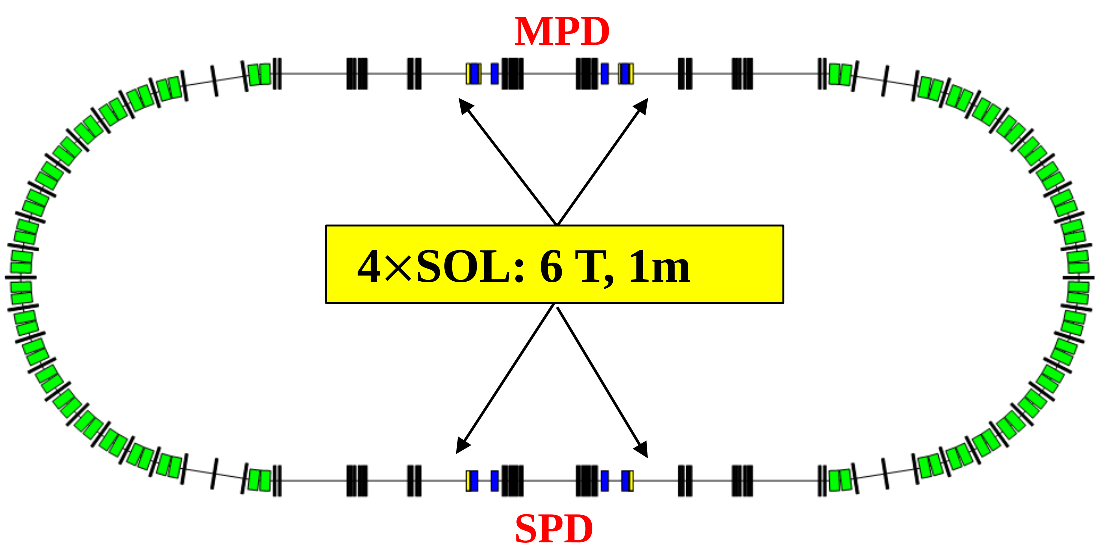
Polarized beams in ST mode at NICA/JINR (1-st stage)



First configuration:
ST mode with the
MPD and 6T-solenoid

p **up to 1.60 GeV/c**
d **up to 0.49 GeV/c**

Experiments on deuteron spin manipulation



Second configuration:
ST mode with four
6T-solenoid

p **up to 3.20 GeV/c**
d **up to 0.98 GeV/c**

ST mode for high precision experiments

1. Compensation of the coherent part of ST resonance spin field:

$$\vec{\boldsymbol{\omega}}_{\text{comp}} = -\vec{\boldsymbol{\omega}}_{\text{coh}}$$

Compensation of the ω_{coh} **makes a realistic collider with errors** nearly equivalent to **an ideal collider without errors**

2. Spin Flipping (SF) System based on SN:

$$\vec{\boldsymbol{n}}_{\text{nav}} = \vec{\boldsymbol{n}}_{\text{nav}}(b_{z1}, b_{z2}), \qquad \boldsymbol{\nu}_{\text{nav}} = \boldsymbol{\nu}_{\text{nav}}(b_{z1}, b_{z2})$$

Both the polarization direction and the spin tune can be adjusted by adiabatically changing the magnetic fields of the SN.

SN prevents resonant beam depolarization by stabilizing the spin tune $\boldsymbol{\nu}_{\mathbf{nav}}$ **= const** during adiabatic adjustment of the polarization direction.

Adiabaticity condition can be written in terms of the spin-flipping time $\boldsymbol{\tau}$ as

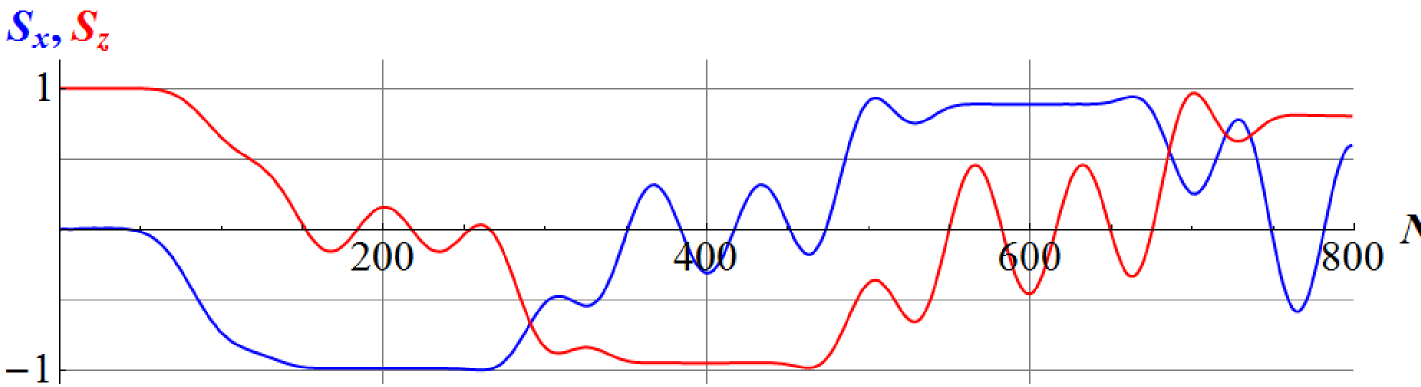
$$\boldsymbol{\tau} \gg \boldsymbol{T}/\boldsymbol{\nu}_{\mathbf{nav}}$$

where $\boldsymbol{T}$ is the particle revolution period.

Spin Tracking of Spin Flip in Nuclotron

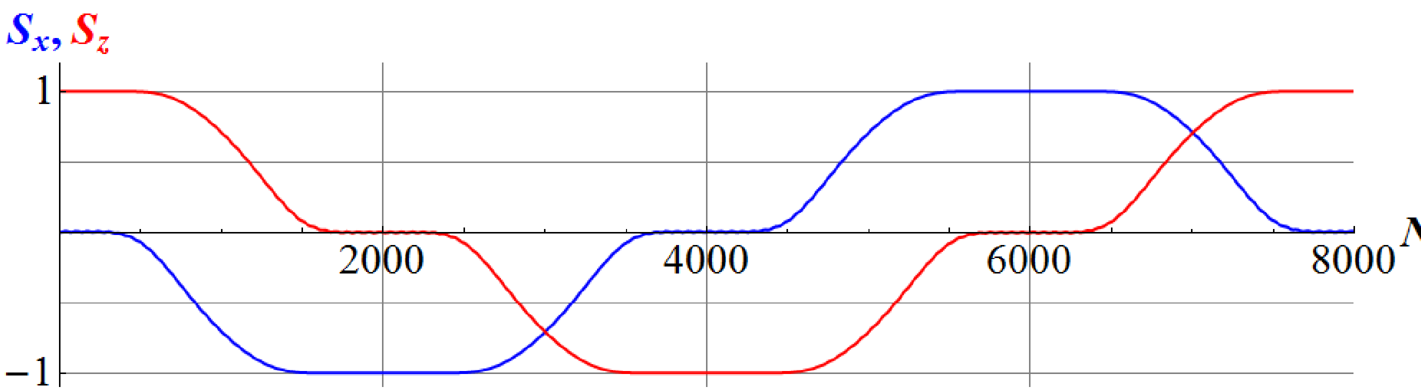
For $\nu_{\mathrm{nav}} = 0.01$ adiabatic condition gives a τ of ~ 1 ms, which corresponds to $N \sim 10^3$ proton turns.

Spin tracking code **ZGOUBI**



Violation of the adiabaticity condition during spin flips ($\gamma G = 2$)

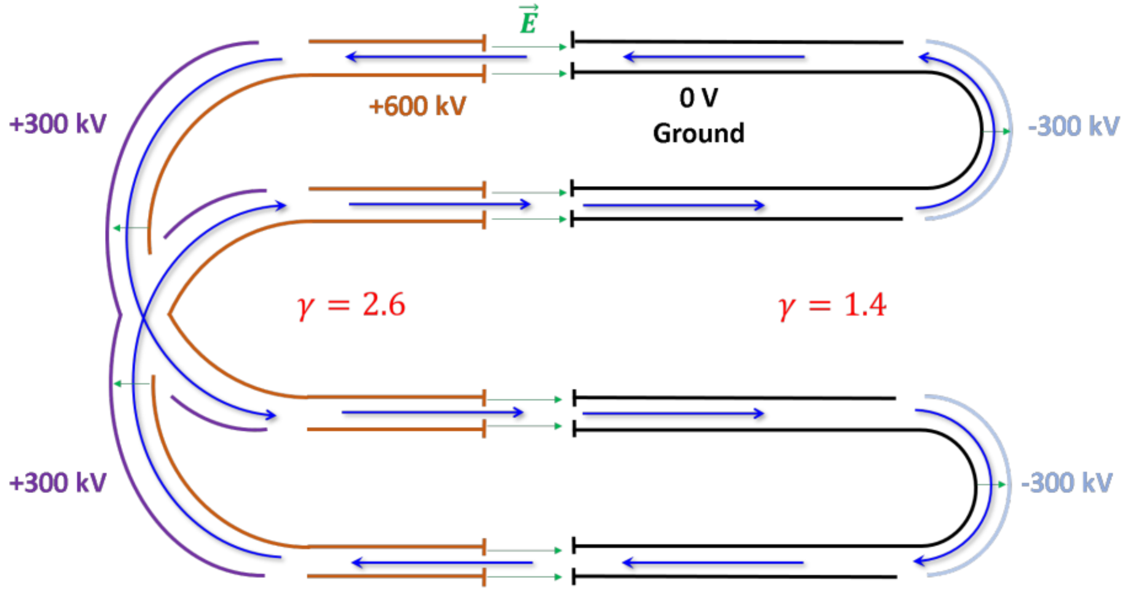
Spin tracking code **ZGOUBI**



Adiabatic spin reversal in Nuclotron ($\gamma G = 2$)

Low Energy Storage Rings for electron EDM search

R. Suleiman, V. S. Morozov, and Y. S. Derbenev, ***On possibilities of high precision experiments in fundamental physics in storage rings of low energy polarized electron beams*** (2021), arXiv:2105.11575 [physics.acc-ph].



For details see talk #50 by R. Suleiman, "EDM in Small Rings" at this conference

It is proposed to search for electron EDM using a figure-8 type storage ring composed of radial and longitudinal electric fields. It is spin transparent to the electron MDM. Spin precesses only due to EDM.

ST configurations may also be considered for proton and deuteron EDM searches.

ST mode at ultra-high energies

It may appear that the area of applicability of the ST concept does not include high energies. Indeed, on one hand, **the compensation condition requires** that the navigator tune must be of the order of the ST resonance strength:

$$\nu_{\mathrm{nav}} \sim \omega$$

and ω **grows proportionally to the energy**:

$$\omega \propto \gamma.$$

On the other hand, the **navigator tune must remain small**

$$\nu_{\mathrm{nav}} \ll 1,$$

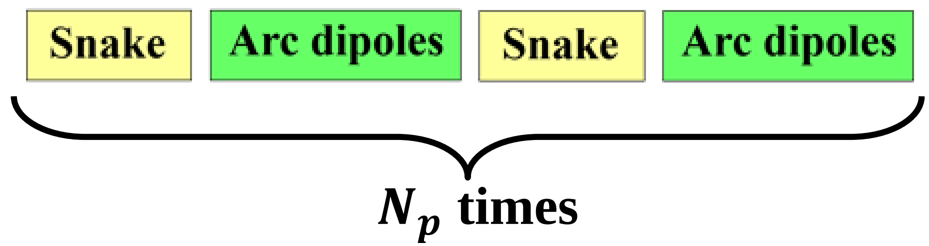
so that perturbation of the orbital beam parameters by the navigator magnetic fields is negligible.

It becomes **unrealistic to meet the condition of $\boldsymbol{\nu_{\mathrm{nav}}}$ being small at sufficiently high energies**.

ST mode at ultra-high energies

One can design a lattice with **a large number of super-periods N_p, each satisfying the spin transparency condition**, i.e. any spin direction repeats at each super-period.

SNs induce the **same spin tune $\boldsymbol{\nu}_{\mathbf{nav}}$ and set the same stable polarization direction in each super-period**.



Total navigator tune $\boldsymbol{\nu}_{\mathbf{tot}} = \boldsymbol{N_p}\,\boldsymbol{\nu}_{\mathbf{nav}}$.

At the same time, the partial navigator tune in the region of a single super-period must be small: $\nu_{\text{nav}} \sim \frac{\omega}{N_p} \ll 1$.

The ν_{tot} can be of the order of a unit or even significantly greater. Thus, the required number of snake pairs is determined by the condition: $\boldsymbol{N_p} \gg \boldsymbol{\omega}$.

The resonance strength at **10 TeV** is then of the order of a unit and **about ten pairs of snakes are sufficient** to provide stable manipulation of the proton polarization.

Conclusion

- Spin transparency is a novel concept of polarization control with weak magnetic fields
- ST expands the toolkit of polarized beam experiments
- It can be implemented in figure-8 rings, racetracks with two Siberian snakes and racetracks at integer spin resonances
- Polarization control is implemented using spin navigators based on solenoids at low energies and transverse fields at high energies
- ST concept can be extended to high energies using a large number of superperiods.
- Several experimental tests are being considered at COSY, NICA and RHIC

Thank you for your attention!